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Comparison of indirect CO_2-emissions of different renewable transport fuels

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Abstract

The European Union's goal is to increase the share of renewable energy sources to 20 per cent and that of liquid biofuels for transport to at least 10 per cent by 2020. Liquid biofuels for transport are, for example, biodiesel and bioethanol. Their use is not assumed to increase CO_2-emissions in the atmosphere. However, production processes of transport fuels need energy causing indirect CO_2-emissions. To evaluate the environmental burden of these biofuels it is important to consider indirect CO_2-emissions in analyses, too. This study defines indirect CO_2-emissions for Digestion process, Bioethanol process, FT-process (Fischer-Tropsch-process) and Bio-SNG-process and compares their environmental burden.

Peer-review under responsibility of Riga Technical University, Institute of Energy Systems and Environment

Keywords: Biomethane; Bioethanol; Biodiesel; Digestion; Fischer-Tropsch-process; Bio-SNG-process

1. Introduction

Carbon dioxide emissions from road traffic have been c. 11.5 million tonnes in Finland in 2013 [1]. This is approximately 19 per cent of total CO_2-emissions in Finland in 2013 [1,2]. EU's goal is to increase the share of renewable energy sources to 20 per cent and that of liquid biofuels for transport to at least 10 per cent by 2020 [3].

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Liquid biofuels for transport include such biofuels as biodiesel and bioethanol. In addition, biomethane can be used as transport fuel. All previous mentioned fuels are renewable transport fuels the use of which is not assumed to increase CO_2-emissions in the atmosphere. These fuels can be produced from different raw materials such as corn, sugar cane, wood-based biomass, as well as urban and industrial waste. Although renewable transport fuels are CO_2-free fuels, their production processes consume electricity and heat. Some production processes also generate heat, and the net heat balance may be either positive or negative. There are several options to produce electricity and heat for production processes. Electricity and heat may be produced using renewable energy sources or fossil fuels. If fossil fuels are used, CO_2-emissions generated in electricity and heat production must be taken into consideration when the environmental burden of renewable transport fuels is assessed. These emissions are usually called indirect emissions.

Energy conversion factors are typically used to consider CO_2-emissions originating from electricity and heat production. Energy conversion factors used in the analysis may have remarkable influence on the results. Factors typically differ between various methodologies and even within the same methodology. Factor values are highly dependent on what energy conversion technologies local electricity and heat production are based on. It is also reasonable to ask whether the factors should be based on average emissions or emissions from marginal production. In addition, the factors are dependent on whether the transport fuel is produced at a stand-alone plant or whether there are options to integrate the production process into some other production plant or an energy system. The previous mentioned reasons partly explain why different studies may give contradictory results on the environmental burden of transport fuels, even if the production process and raw materials are the same.

This study calculates indirect CO_2-emissions for four transport fuel production processes which are Digestion process, Bioethanol process, FT-process (Fischer-Tropsch-process) and Bio-SNG-process. Digestion and bioethanol processes produce biomethane and bioethanol from waste, respectively whereas FT-process and Bio-SNG-process produce biodiesel and biomethane from wood-based biomass, respectively. Instead of emission factors, this study presents direct calculation equations which give indirect CO_2-emissions per tonne of end product. Calculation equations take into account the energy conversion technologies used to produce electricity and heat as well as whether the production process is integrated into another energy system or not. CO_2-emissions generated in transportation of the renewable fuels are not considered. To compare CO_2-emissions between transport fuels produced in previous mentioned processes, CO_2-emissions per vehicle kilometer are defined for each fuel.

This study has been made in collaboration between Aalto University and Gasum in the EFEU-project (Energy Efficient Energy Use). Analysis methods have been discussed in six meetings/mini seminars which were attended by representatives from both Aalto and Gasum.

2. Methods

2.1. Description of processes

Figures 1−2 show main material flows and energy in- and outputs for transport fuel production processes studied in this paper. Material flows and energy in- and outputs are based on references [4−11]. These values are case-dependent and may vary between the same production processes depending on the raw-material, process configuration, chosen technology, process plant location, etc. For example, the electricity inputs for digestion processes (excluding gas up-grading) are reported to be 0.6 MWh/t_{biogas} and 0.75 MWh/t_{biogas} in [4] and [5], respectively. References used for material flows and energy in- and outputs in each process are reported in the captions below Figs. 1 and 2.

Both the FT-process and Bio-SNG-process produce hot water and steam when unit processes or process streams are cooled down. In Fig. 2, both processes always produce high pressure steam (100 bar, 500^{o}C) when possible. If the temperature of the unit process or process stream is too low, middle pressure steam (10 bar, 190^{o}C) or hot water is produced (3 bar, 100^{o}C). The FT-process generates middle pressure steam (MP-steam) after the FT-synthesis unit, and this steam is utilized in gasification and reforming+shift units. The Bio-SNG-process generates hot water in several unit processes. The hot water is primarily used in the drying unit and possible excess heat is utilized outside the process if possible. Pressure swing adsorption (PSA) is used for Gas up-grading when needed.

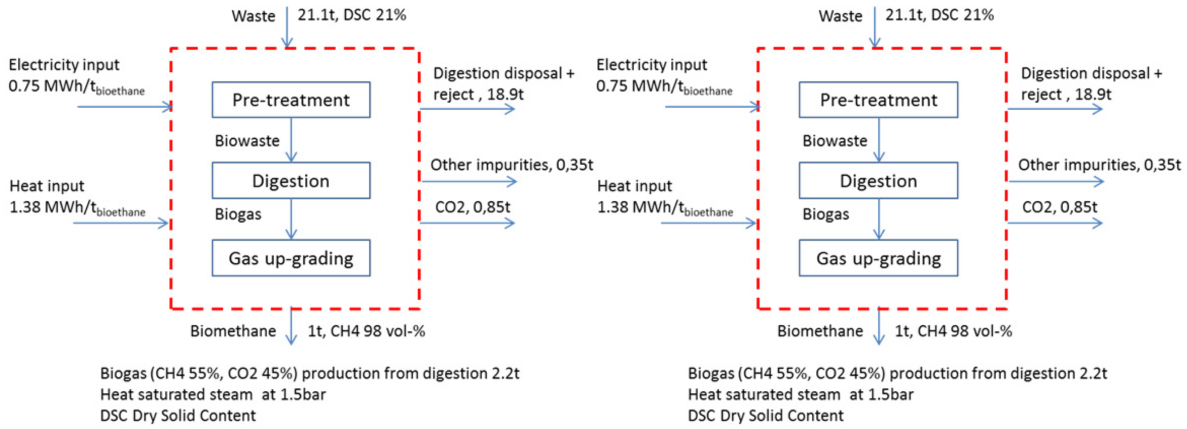

Fig. 1. Main material streams and energy inputs in biomethane production from waste and bioethanol production. Material streams and heat inputs in digestion are based on [7] and electricity input (0.25MWh/$t_{biomethane}$) in gas up-grading on [6] Electricity inputs in pre-treatment and digestion (0.5MWh/$t_{biomethane}$) have been evaluated based on references [4, 5, 7, 8]. Material streams and electricity and heat inputs in ethanol production are based on reference [9].

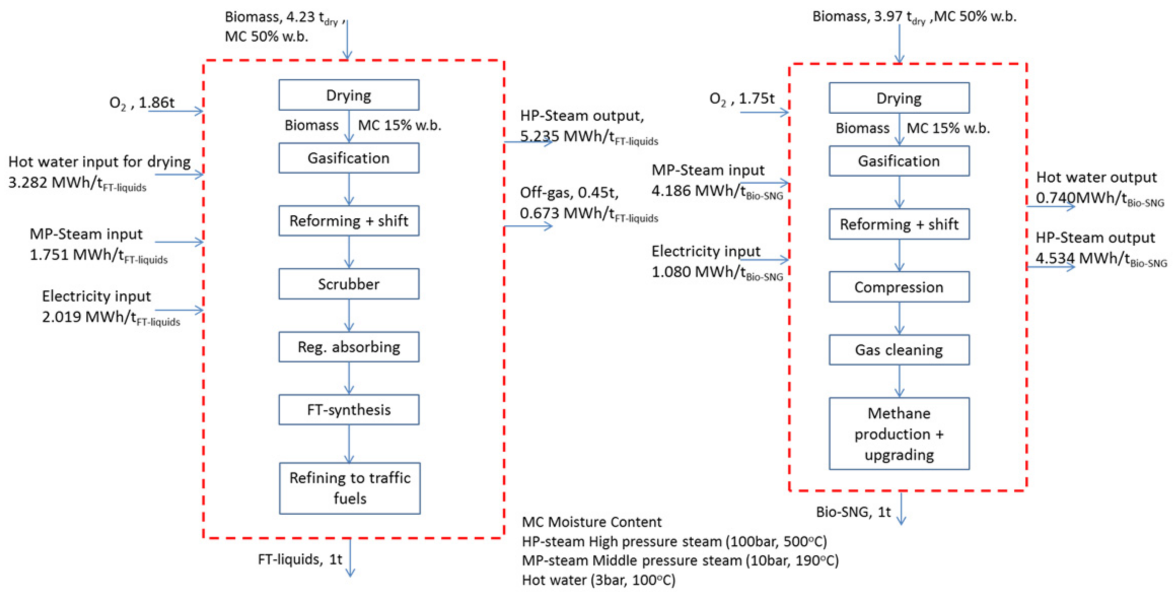

Fig. 2 Main material streams and energy inputs and outputs for FT- and Bio-SNG-process. Material streams and electricity input in FT-process are based on reference [10] and heat in- and outputs on [10, 11]. Material streams and energy in- and outputs in Bio-SNG are based on [11].

2.2. Calculation of CO_2-emissions

Figures 1−2 show that all processes need electricity. Digestion and ethanol production processes also need heat. Instead, FT- and Bio-SNG-processes both consume and generate heat. In addition, biomethane and off-gas are obtained as by-products from ethanol production process and FT-process, respectively. To analyze CO_2-emissions from each process, two different Cases are studied. **In the first Case**, all production processes are stand-alone plants, and electricity and heat are produced separately (Fig. 3a). **In the second Case**, all processes are integrated into a CHP plant, which produces heat for processes and district heating (Fig. 3b). The CHP plant is assumed to produce so much district heat that additional fuel is always needed regardless of how much steam or fuel are obtained from the production processes of transportation fuels.

Fig. 2 shows that heat outputs and off-gas output from the FT-process and Bio-SNG-process exceed heat inputs into the processes. This means that there is no need for heat production when electricity and heat are produced separately in Case 1. The ethanol production process generates large amounts of biogas as a by-product. By combusting the biogas in a separate heat boiler, the heat input of the process can always be covered, and therefore there is no need to purchase any fuel outside the mill. Actually, the boiler generates more heat than needed by the ethanol production process, and the excess heat could be used for some other process (e.g. district heating) if possible.

CO_2-emisssions are released as by products in all production processes (see Fig. 1). For example, gas-upgrading and fermentation generate CO_2-emissions. These emissions are not considered in calculation of indirect CO_2-emissions because waste and biomass are CO_2-free material streams.

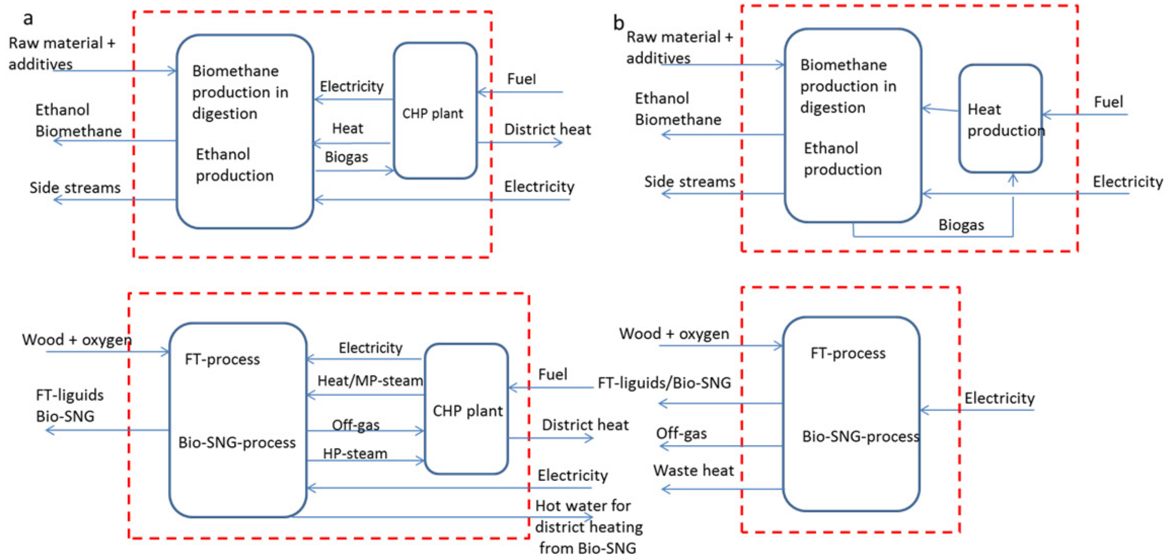

Fig.3 (a) balance boundaries when all processes are stand-alone plants (Case 1); (b) balance boundaries when all processes are integrated into a CHP plant (Case 2). Biogas and off-gas are obtained from ethanol production process and FT-process, respectively.

2.2.1. Calculation of CO_2-emissions of the production process when processes are stand-alone plants, Case 1

When electricity and heat are produced separately for stand-alone plants, energy inputs of the processes are covered as follows:

Digestion: Electricity is produced in a coal condensing power plant or by using some form of renewable electricity production (e.g hydro power, biomass or solar power). Heat is produced in a separate heat boiler by combusting either biomass or peat.

Ethanol production: Electricity is produced at a coal condensing power plant or using some form of renewable electricity production. Heat is produced in a separate heat boiler by combusting either biomass or peat. Biogas from the ethanol production process is combusted in a heat boiler to generate heat for the production process. Combustion of biogas covers all heat demand and the excess heat is not utilized (i.e. it is waste heat).

FT-process: Electricity is produced at a coal condensing power plant or by using some form of renewable electricity production. Heat generated in the FT-process (HP-steam, off-gas) exceeds heat demand of the process. There is no need for a separate heat boiler. Excess heat from the process is not utilized. Off-gas consists of mainly light hydrocarbons (1-4 carbon atoms), carbon dioxide and unconverted hydrogen and carbon monoxide. In this case, the heating value of off-gas is low (see Fig. 2) due to low CO_2 removal efficiency.

Bio-SNG-process: Electricity is produced at a coal condensing power plant or using some form of renewable electricity production. Heat generated in the Bio-SNG-process (HP-steam, hot water) exceeds heat demand of the process. There is no need for a separate heat boiler.

CO_2-emissions [$t_{CO2}/t_{end\text{-}product}$] generated in the production process are calculated as follows:

$$m_{CO2} = \frac{Q_{heat}}{\eta_{heat\ boiler}} b_{heat\ boiler} + \frac{P}{\eta_{con}} b_{con} , \qquad (1)$$

where Q_{heat} – is heat input into the process; P – electricity input into the process; $\eta_{heat\ boiler}$ – efficiency of heat boiler; η_{con} – efficiency of condensing power plant; $b_{heat\ boiler}$ – emission factor of fuel in heat production (t_{CO2}/MWh); b_{con} – emission factor of fuel in electricity production.

2.2.2. Calculation of CO_2-emissions of the production process when processes are integrated into a CHP plant and possible district heating system, Case 2

When all processes are integrated into a CHP plant, energy inputs and heat integration between the production process and the CHP plant are carried out as follows:

Digestion: All heat is produced at the CHP plant. If the electricity produced at the CHP plant does not cover electricity demand of the process, the rest of the electricity is produced at a coal condensing power plant or using some form renewable electricity production.

Ethanol production: All heat is produced at the CHP plant. If the electricity produced at the CHP plant does not cover electricity demand of the process, the rest of the electricity is produced at a coal condensing power plant or using some form of renewable electricity production. Biogas from the ethanol production process is combusted at the CHP plant.

FT-process: District heating water (3 bar, 100 °C) from the CHP plant is used for drying. MP-steam generated in the process is used in gasification and reforming+shift unit and the rest of the MP-steam demand (1.751MWh/t) is covered producing it at the CHP plant. HP-steam generated in the process is used at the CHP plant by letting it expand through the turbine. Off-gas from the process is combusted at the CHP plant. If the electricity produced at the CHP plant does not cover electricity demand of the process, the rest of the electricity is produced at a coal condensing power plant or using some form of renewable electricity production.

Bio-SNG process: Hot water from the Bio-SNG process is used for drying and the rest of the water is fed into the district heating system. All MP-steam is generated at the CHP plant. HP-steam generated in the process is used at the CHP plant by letting it expand through the turbine. If the electricity produced at the CHP plant does not cover electricity demand of the process, the rest of the electricity is produced at a coal condensing power plant or using some form of renewable electricity production.

CO_2-emissions [$t_{CO2}/t_{end\text{-}product}$] generated in production process are calculated as follows:

$$m_{CO2} = \left(\frac{(1+\alpha_{hot\ water})Q_{hot\ water} + (1+\alpha_{MP\text{-}steam})Q_{MP-steam} - (1+\alpha_{DH})Q_{DH}}{\eta_{CHP\ plant}} - \frac{Q_{HP\text{-}steam}}{\eta_{CHP\ boiler}} - \Phi_{off\text{-}gas} \right) b_{CHP\ plant} + \left(\frac{(P - \alpha_{hot\ water}Q_{hot\ water} - \alpha_{MP\text{-}steam}Q_{MP-steam} + \alpha_{DH}Q_{DH})}{\eta_{con}} \right) b_{con} \tag{2}$$

where $\alpha_{hot\ water}$ – power-to-heat ratio in hot water heat generation at a CHP plant; $Q_{hot\ water}$ – hot water input into the production process; $\alpha_{MP\text{-}steam}$ – power-to-heat ratio in the middle pressure steam generation at a CHP plant; $Q_{MP\text{-}steam}$ – middle pressure steam input into the production process; α_{DH} – power-to-heat ratio of the CHP plant in district heat generation; Q_{DH} – district heat generation in the production process; $Q_{HP\text{-}steam}$ – high pressure steam output from the production process into the CHP plant; $\Phi_{off\text{-}gas}$ – energy content of off-gas from the production process (only FT-process); $\eta_{CHP\ plant}$ – efficiency of the CHP plant; $\eta_{CHP\ boiler}$ – efficiency of the boiler at the CHP plant; P – electricity input into the production process; η_{con} – efficiency of the condensing power plant; $b_{CHP\ plant}$ – emission factor of the fuel in CHP production; b_{con} – emission factor of the fuel in separate power production.

Calculation principles of Eq. (2) are based on [12].

Both FT- and Bio-SNG-processes generate HP-steam into the CHP plant. This reduces the fuel input into the CHP plant. HP-steam from the FT- and Bio-SNG-process is generated using CO_2-free fuel (biomass). If the CHP plant combusts fossil fuels, heat integration reduces CO_2-emissions at a CHP plant as Eq. (2) shows.

2.2.3. Calculation of CO_2-emissions when end-products are used as transport fuels

When end-products are used as transport fuels, the CO_2 emissions per km are calculated as follows:

$$m_{CO2} = E_{car} q_{fuel} \varepsilon_{CO2} \tag{3}$$

where E_{car} – denotes the specific energy consumption per vehicle kilometer of a car (MJ/km); q_{fuel} – lower heating value of the traffic fuel; ε_{CO2} – specific CO_2 emission of the traffic fuel.

Specific CO_2-emissions are calculated using Eqs. (1) and (2).

2.3. Input data for calculations

Technical performance parameters of power plants and other input data necessary to calculate CO_2-emissions are shown in Tables 1 and 2. The specific energy consumption of the car represents the average energy consumption per vehicle kilometer in Finland. The consumption has been taken from [1].

Table 1. Input data for defining CO_2-emissions of the production processes

Input data		
Boiler efficiency at the CHP plant	0.9	
Efficiency of the CHP plant, η_{CHP}	0.9	
Power-to-heat ratio in hot water production, $\alpha_{hot\ water}$	0.5	
Power-to-heat ratio in MP-steam production, $\alpha_{MP\text{-}steam}$	0.2	
Power to heat ratio in DH-production, α_{DH}	0.2	
Efficiency of condensing power plant	0.4	
Emission factor for coal	340.28	kg/MWh
Emision factor for peat	381.26	kg/MWh
Emission factor for biomass	0	kg/MWh

Table 2. Input data for defining CO2-emissions per vehicle kilometer

Input data		
Specific energy consumption, E_{car}	2.5	MJ/km
Lower heating value of biomethane	49.0	MJ/kg
Lower heating value of ethanol	26.6	MJ/kg
Lower heating value of biodiesel	41.5	MJ/kg

3. Results

Fig. 4 shows CO_2-emissions when processes are stand-alone plants (Case 1) and integrated into a CHP plant (Case 2). Results in Fig. 4 show how much CO_2-emissions change compared to the situation where the end-products are not produced. Fig. 5 shows total fuel inputs in electricity and heat production for each process in Cases 1 and 2. CO_2-emission between each processes are not comparable in Fig. 4, because end-products are not the same. To compare CO_2-emission between each production processes all end-products are used as transport fuel and emission are calculated in unit gram of CO_2 per vehicle kilometer. A car using gasoline has been used as a reference case. Results of the comparison are shown in Fig 6. For some production processes (see Case 2, Fig.6) CO_2-emissions may even reduce. This happens because CO_2-free side-streams from the production processes can be integrated into the CHP plant in which case the use of fuel can be reduced in the plant. If the fuel is a fossil fuel, CO_2-emissions also reduce.

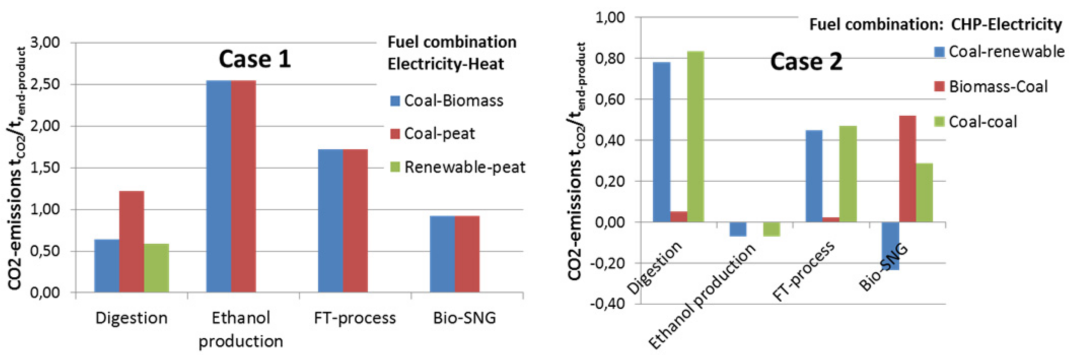

Fig. 4. CO_2-emissions ($t/t_{end\text{-}product}$) in Cases 1 and 2 (see cases on page 4). In case 2, electricity below fuel combination means separate electricity production which is needed if the CHP production does not cover electricity demand of the production process.

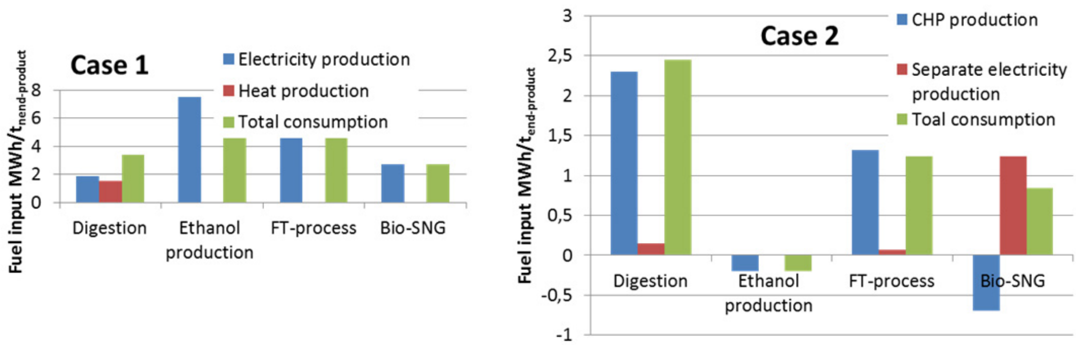

Fig. 5. Fuel inputs in electricity and heat production for Cases 1 and 2 (see cases on page 4). In Case 2, electricity below fuel combination means separate electricity production which is needed if the CHP production does not cover electricity demand of the production process.

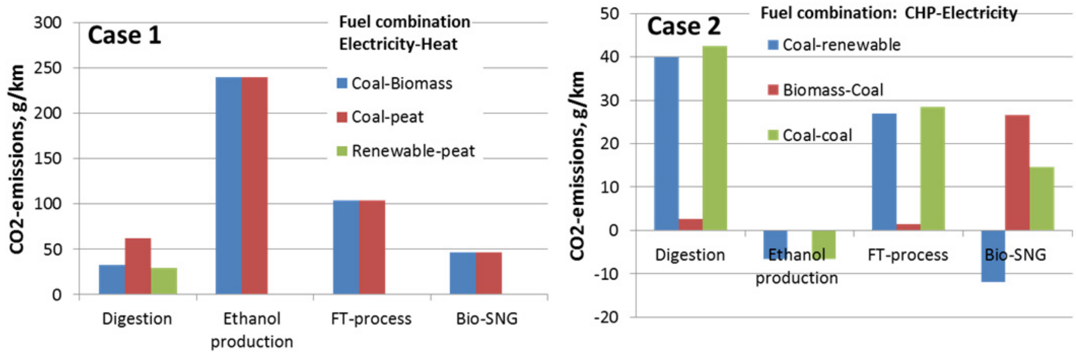

Fig. 6. Comparison of CO_2-emissions (g/km) between different end-products when they are used as traffic fuels. Average CO_2-emissions for a gasoline driven car are 165g/km [1].

4. Conclusions

In most cases, production processes of renewable transport fuels generate less indirect CO_2-emissions than direct CO_2-emissions from a gasoline driven car. The only exception is bioethanol when it is produced at a stand-alone plant. When biomass is used as a raw material, the Bio-SNG process seems to be a more environmentally friendly process than the FT-process apart from the case where the CHP plant combusts also biomass and separate electricity production is based on coal combustion. In general, results indicate that it is possible to reduce CO_2-emission originating from transport when either waste or wood-based biomass is used as raw material to produce renewable transport fuels.

Results also suggest that integration of the production process into a CHP plant and a district heating system in the case of Bio-SNG-process is beneficial from the viewpoint of CO_2-emissions. Even though CO_2-emissions are higher in few cases for the integrated system, it is reasonable to conclude that the production process should be integrated into a CHP plant and possibly into some other energy production system (e.g. district heating system) as well. It is also notable that CO_2-emissions may even reduce compared to the current situation as a result of integration in some cases.

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